Acoustic soil and rock sounding

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Abstract. A new method for identification of soil and rock materials by acoustic measurements during soil-rock probing is presented. A triaxial geophone is installed at 4 m distance from the borehole and vibration signals are recorded during the drilling process. The vibration amplitude reveals information of the strength and stiffness of the penetrated soil and rock layers. The vibration amplitude generally decreases with depth but increases when stiff or hard layers are encountered. The frequency content of the vibration signal is a useful indicator of the characteristics of the penetrated material. By determining the frequency spectra during drilling, it is possible to identify different soil and rock layers. The vibration measurement can be synchronized with the drilling depth measurement and displayed together with conventional drilling parameters. Seismic measurements are easy to perform and do not interfere with the drilling process.

Key words: acoustic sounding, frequency, penetration testing, spectrogram, vibration velocity

Introduction

Geotechnical field investigations provide important information for geotechnical design. However, it can be difficult to obtain reliable geotechnical information, especially in hard soils, soft rock or treated ground (improved by deep soil mixing or grouting) due to the limited penetration capacity of conventional geotechnical field investigation methods, such as the cone penetration test (CPT) or the dilatometer (DMT). On the other hand, conventional rock drilling equipment is not sufficiently sensitive to investigate stiff or compact soil layers. The availability of electronic measuring and powerful data acquisition systems has opened new possibilities. One such application is soil rock sounding (SRS), which is used in Sweden to identify dense soil layers, boulders or the transition from hard soil to fractured rock. However, SRS investigations can only provide a rough estimate of the existence of fractured rock. Guidelines regarding the execution and interpretation of SRS investigations have been published by the Swedish Geotechnical Society, SGF (2012), *Method statement for soil rock sounding.*

SRS sounding is divided into three classes. Class 1 (Jb-1) is the basic method and can be executed by a conventional drill rig without any specific recording of drilling parameters. Class 2 (Jb-2) is used for more detailed investigations of soil layers. For a reliable identification of soil and rock boundaries it is necessary to consider in the analysis several drilling parameters, such as penetration (sinking) speed, thrust, rotation speed and pushing force. The method can also be used to identify boulders or to determine the soil-rock interface. Another application is to determine the driveability of piles or sheet piles. The standardized drilling and registration equipment is an essential part of Jb-2. SGF has published a guidance document to assist geotechnical engineers in the interpretation of Jb-2 drilling, SGF 2015 („Improved interpretation of results from soil rock sounding/MWD"). However, it can be concluded that on many occasions the results of SRS are difficult to interpret reliably.

This paper presents a new concept where seismic (acoustic) measurements are carried out in combination with SRS. The advantage of this concept is that seismic measurements can be carried out continuously during the drilling process. The obtained seismic parameters are independent of conventional drilling parameters and therefore offer an additional source of information which can help to identify soil and rock formations.

Acoustic sounding

Seismic measurements during penetration testing

Seismic measurements can be combined with different types of penetration tests. The first application of seismic observations in connection with penetration testing was probably the Swedish Weight Sounding Test (WST). A major problem in Sweden is the identification of layers of silt and sand embedded in soft, sensitive clay. Also the transition from a clay deposit into underlying sand and till is important information. Figure 1 shows a penetration test in 1925 in the Gothenburg region of Sweden. The foreman (to left) is required to touch the top of the sounding rod in order to detect rod vibrations which are caused when the tip of the penetrometer tip encounters granular soil layers.

Fig. 1. Swedish Weight Sounding Test (WST) anno 1925, Gothenburg, Sweden. The foreman (left) is required to touch the top of the sounding rod to detect vibrations when sounding tip penetrates into sand layer

Soil Rock Sounding

SRS is carried out by a hydraulic drill rig, using rotary and percussive action. The hammer operating frequency ranges typically between 1100 and 1400 blows/min (18 to 24 Hz). The hammer energy is typically 2200 J and the pushing force 35-40 kN at a drill rotation speed of at least 80 rpm. An important advantage is that seismic measurements can be carried out without interfering with the drilling process.

During drilling, the drill bit emits vibrations which are transmitted to the surrounding soil as vibrations (and sound). The seismic signal can be recorded at the ground surface by vibration sensors, such as geophones (vibration velocity) or accelerometers (acceleration), Fig. 2.

Modern data acquisition systems can record vibrations within a wide frequency range and over an extensive time period (hours), sufficiently long to cover the drilling process in several boreholes.

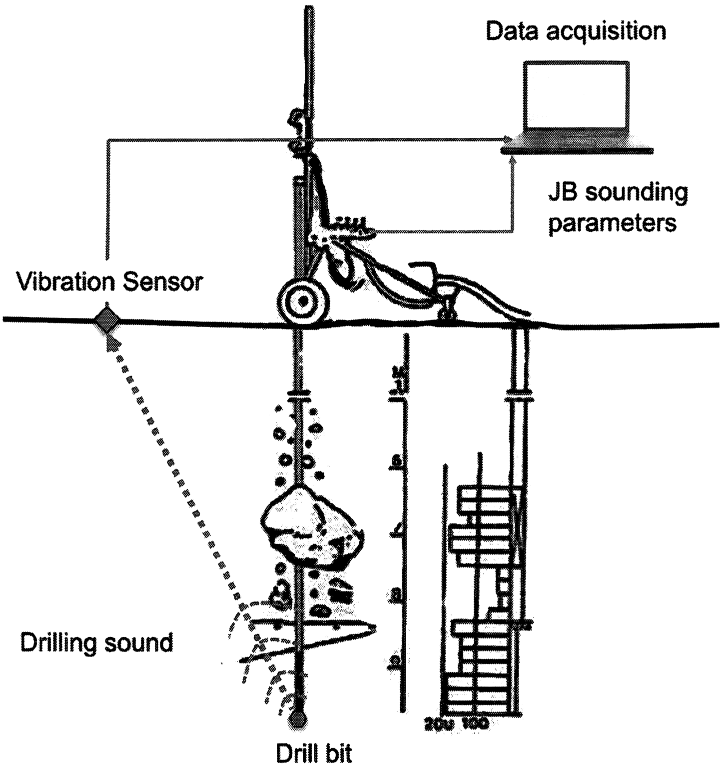


Fig. 2. Acoustic measurements during Soil Rock Sounding

Equipment and measuring procedure

When drilling through soil and rock layers, the amplitude and frequency content of the seismic signal can vary within a wide range. An objective of the present investigation was to determine which type of vibration sensor and measurement distance was best suited for the purpose of identifying soil and rock layers. The seismic signals were recorded by a 16-channel data acquisition unit.

Initial tests were performed with triaxial geophones at five different distances from the borehole (1, 2, 4, 8 and 12 m). It was found that the measured vibration velocity in all boreholes showed similar vibration characteristics (amplitude and frequency content). Based on extensive trials, it was found that consistent results could be obtained using a triaxial geophone located at the ground surface at 4 m distance from the borehole. The testing arrangement used in this investigation is shown in Fig. 3.

Figure 4 shows a typical test set-up of seismic measurements. The triaxial geophone was placed at 4 m distance in front of the drilling rig.

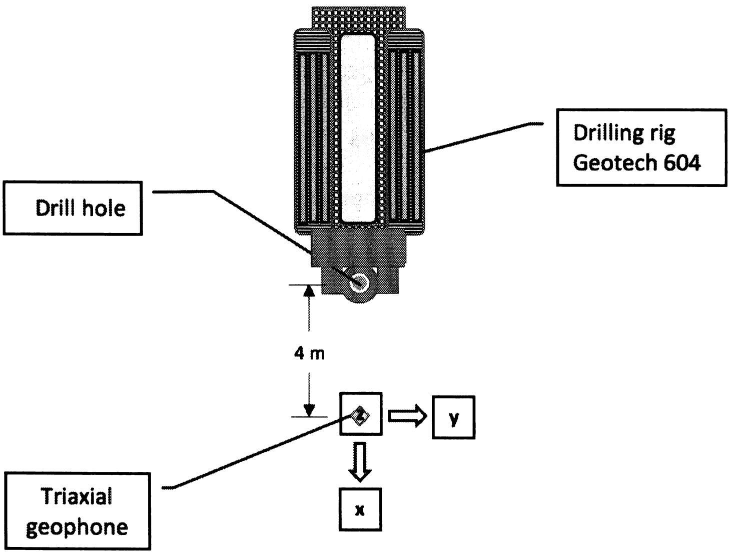


Fig. 3. Measuring set-up of seismic measurements during soil-rock drilling.
The symbols *x*, *y* and *z* show the measuring direction of the geophone

Fig. 4. Testing arrangement with drill rig type Geotech
and triaxial geophone at 4 m distance from drill hole

Presentation of measurement results

During the test, the three components (vertical: *z*, longitudinal: *x* and transversal: *y*) of vibration velocity were recorded continuously as a function of time. As part of the development project, the seismic measuring system was modified to also record the penetration depth of the drill. Thus it was possible to present seismic measurements as a function of depth, i.e. of other drilling parameters. The following seismic parameters were evaluated, based on the seismic measurements:

1. Peak vibration velocity (mm/s) as function of time and depth.
2. Time signal (mm/s) during time intervals of 5 seconds.
3. Frequency spectra for selected time intervals within a frequency range of 0 to 50 Hz.
4. Spectrogram showing the continuous variation of frequency content as function of time or depth.

Acoustic measurements were carried out at three locations in the Stockholm region. However, in the present paper, only the results of the final test site (Åkersberga) are presented. These are considered the most illustrative of the three tests.

Seismic field tests

Geotechnical conditions

The geotechnical conditions were initially investigated by WST, which gives reliable information in soft and loose soils. The penetration resistance is measured in terms of half turns per 20 cm (ht/0.20 m). Below a dry surface crust (stiff clay) down to 2.5 m, soft clay is found. Below the clay layer, at 7.5 m depth, an approximately 3 m thick layer of granular material (till) follows. Weight sounding had to be terminated at 11 m depth. Seismic measurements were performed in connection with Jb-2 tests. The results of WST and SRS are shown in Fig. 5. The following parameters were recorded: sinking speed of drill (mm/s), pushing force (kN), drill rotation speed (rpm), hammer pressure (MPa) and engine pressure (MPa).

SRS shows that the pushing force varies close to the ground surface between 2 and 3 kN but decreases in the underlying soft clay to 1 kN. The sinking speed of the drill is high, exceeding 40 mm/s. At 7.5 m depth, the pushing force increases from 1 to 5 kN. The hammer rotating speed increases at 8.5 m depth to 70 rpm. Rock is encountered at 11 m depth where the sinking speed decreases clearly to about 10 mm/s. However, the rock formation includes also softer layers (fracture zones) where the sinking speed increases (up to 20 mm/s).

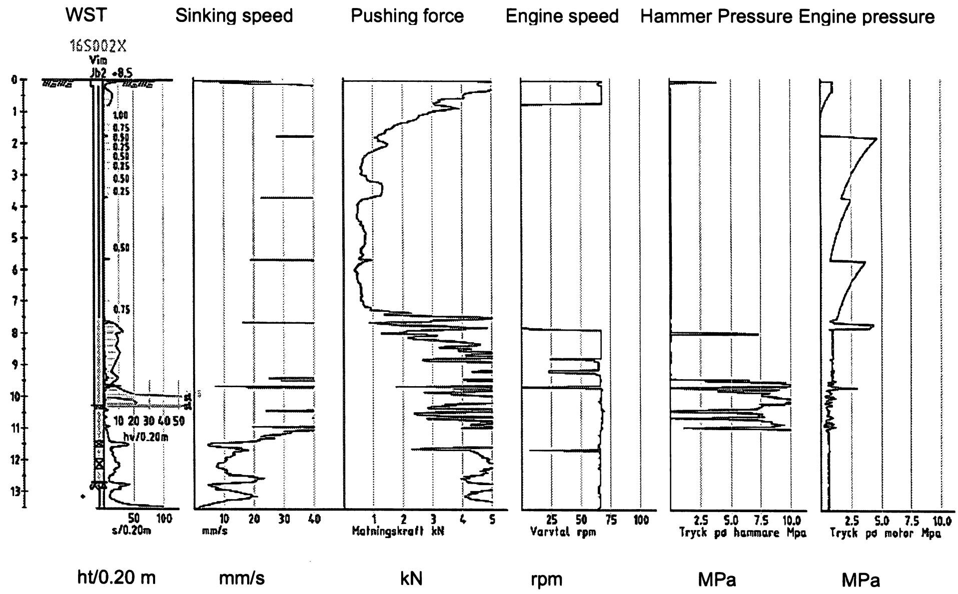


Fig. 5. Results of SRS Class 2 (Jb 2) and Swedish Weight Sounding.
Shown to the left are the results of WST (half-turns/20 cm)

Vibration velocity

The seismic signal was recorded at 4 m distance from the drill rig in three directions, Fig. 6. The drill penetration rate was recorded simultaneously. During the joining of drill rods (approximately every 2 m), the seismic recordings were interrupted. However, the time for joining has been removed in the figure so that only penetration is shown. The top diagram shows drilling depth (m) as a function of time. It can be seen that the drilling speed decreases markedly at about 100 s. The below diagrams show the radial (x), transversal (y) and vertical (z) components of the vibration velocity. The measurements were terminated after 400 s active penetration time (7 minutes). It is interesting to note that the hammer generates in the present case about twice as strong radial vibrations compared to the vertical and transversal components. This indicates that when penetrating into stiff soil and rock, vibrations are generated primarily due to shear waves.

Generally, during the first 100 seconds while penetrating soft clay, the vibration velocity is low. However, also without hammer rotation, vibrations are generated which indicate variable geological conditions. The radial vibration component appears to respond most distinct to changing ground vibrations. It should be noted that in general, the vibration velocity decreases with increasing penetration depth. Still, distinct and clear vibration signals are obtained from depths exceeding 10 m.

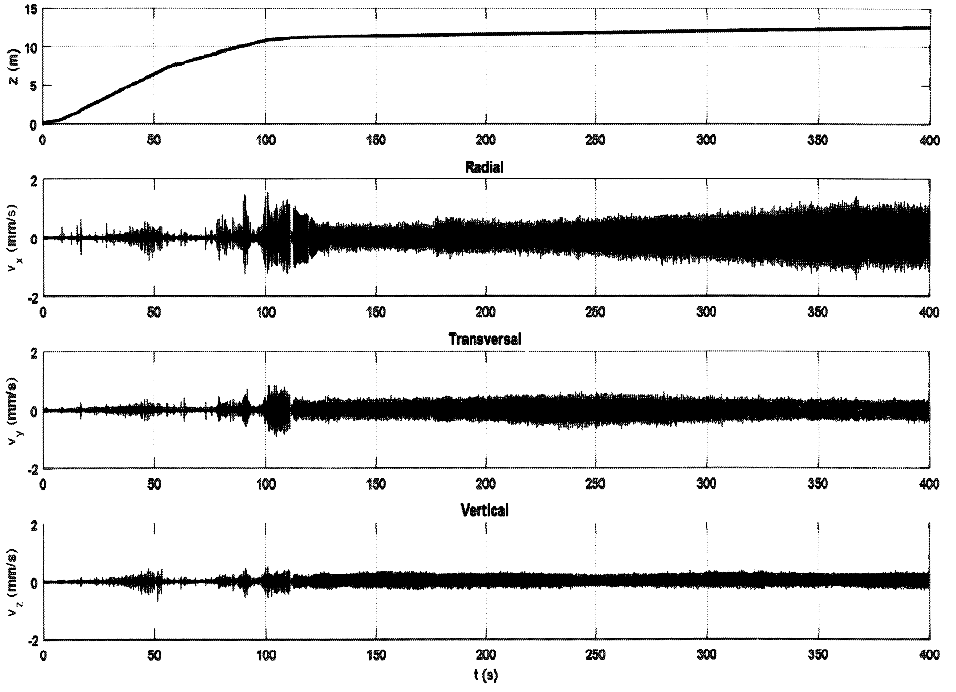
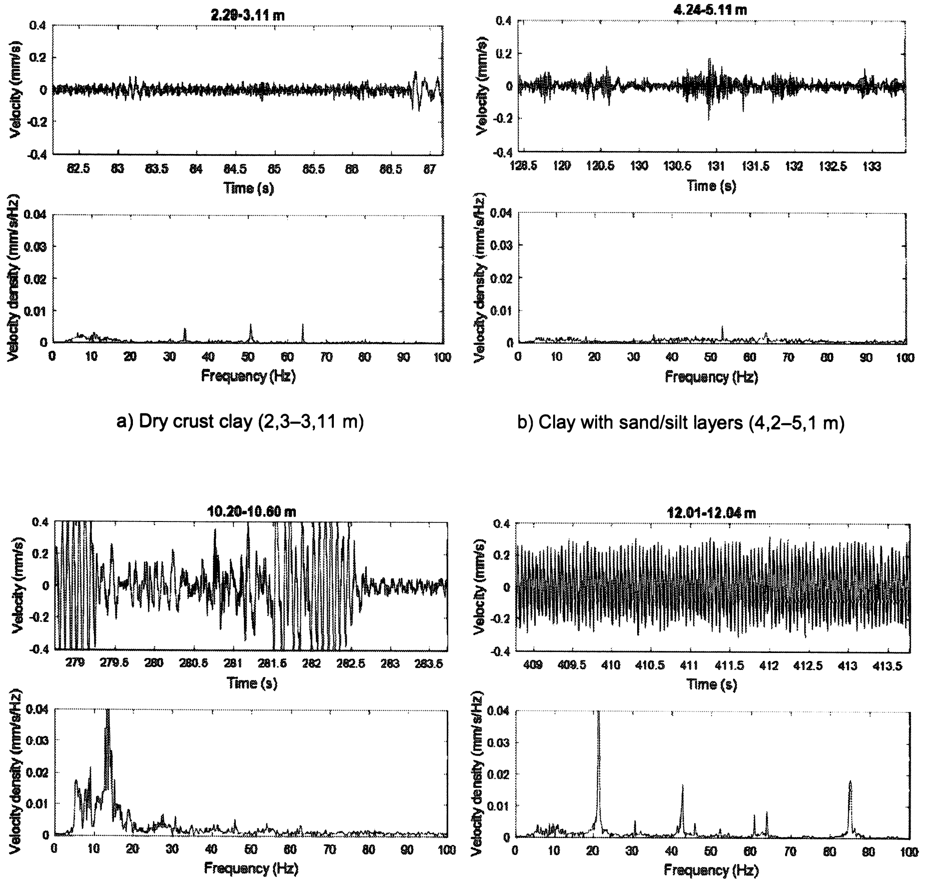


Fig. 6. Three components of vibration velocity and drill depth as function of time (s)

Frequency content

The vibration frequency is a useful indicator of the material which is penetrated by the drill and FFT analyses has been conducted for selected vibration signals. Fgure 7 shows short time histories of vertical vibration velocity and corresponding frequency spectra in different soil layers and rock. The vibration amplitude increases with the stiffness of the penetrated material. In the dry crust (a) and the clay layer (b), the vibration amplitude is very low and the frequency spectra show no distinct peaks. When the drill penetrates into the friction soil, a significant increase in vibration velocity can be observed. Also, the frequency spectrum shows distinct peaks within a range of 5 to 15 Hz. When the drill enters rock, a distinct frequency emerges (21 Hz) which corresponds to the hammer operating frequency (1250 rpm). It can be concluded that the shape of the frequency spectra (dominant frequencies) reflects the penetrated material.



a) Dry crust clay (2,3–3,11 m)

b) Clay with sand/silt layers (4,2–5,1 m)

c) Friction soil (till?) (10,2–10,6 m)

d) Rock (12,01–12,04)

Fig. 7. Vertical vibration velocity and corresponding frequency spectra in different soil layers and rock. Note that the frequency range is 0-100 Hz and that the operating frequency of the drill is 21 Hz (1250 rpm)

Spectrogram

A spectrogram is a visual representation of the spectrum of frequencies in a vibration signal. Spectrograms can be obtained from a continuous signal and plotted vs. time or depth. This is a convenient method of showing the variation of dominant frequencies during SRS. Figure 8 shows a comparison of sounding results (SRS and WST) with vibration velocity and frequency spectrogram. The main soil layers were identified based on WST. The highest values of particle velocity are shown in the spectrogram in bright colours. Low amplitude values are displayed in dark blue.

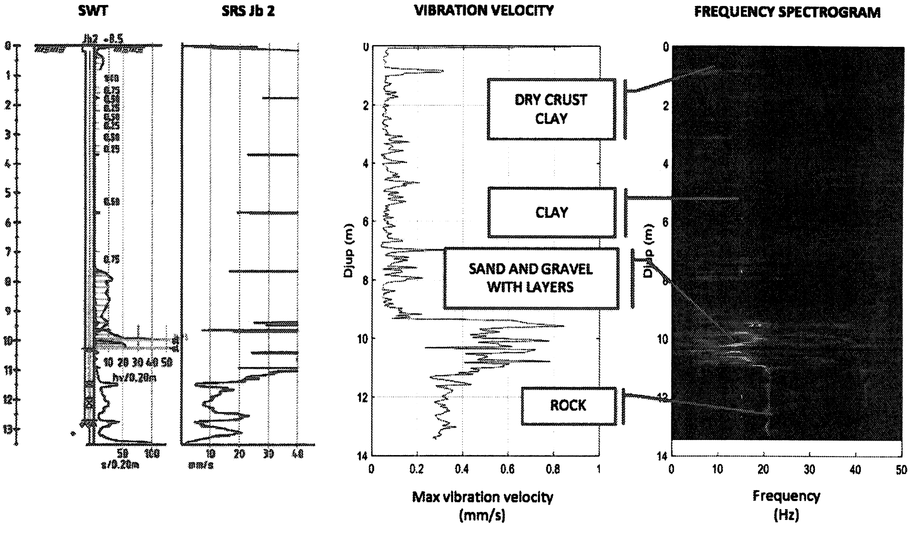


Fig. 8. Summary of acoustic SRS (Jb 2) with drilling parameters, vibration velocity and frequency spectrogram. Detailed frequency spectra for representative soil layers and rock are shown in Fig. 7. Soil layer identification is based on WST

Summary and conclusions

The results from seismic measurements in connection with soil rock soundings (site Åkersberga) are presented. The main objective of the investigation was to provide additional information which can help to identify stiff soil layers, boulders and rock. Material interpretation from SRS Class 2 (Jb-2) data is based primarily on the sinking speed of the drill and the pushing force applied to the drill. Also the rotation speed is considered. Seismic measurements provide additional information which can help to distinguish different soils and rock. An important advantage of acoustic penetration testing is that measurements can be carried out independent of the drilling operation.

Based on the experience from previous investigations it was found that 4 m is a suitable measurement distance from the drilling point. All three components of the vibration velocity are recorded, as well as the drilling depth. Based on the above presented data, the following conclusions are drawn:

- The vibration velocity increases significantly when hard layers are encountered.
- The variation of vibration velocity in the time histories reflects the stratification of the penetrated material.
- In very soft soils (clay), very low vibrations are generated.
- The frequency content is a useful indicator of the type of penetrated material.
- In granular soils (sand, gravel or till), a broad frequency spectrum is obtained, ranging typically between 5 and 15 Hz.

- In rock, the frequency spectrum shows a distinct peak at the hammer operating frequency.
- A powerful way of presenting the results of acoustic measurements is by means of frequency spectrograms.
- The effect of engine noise is negligible.

Acoustic soil-rock sounding was performed only at three locations in the Stockholm region. Therefore, the results need to be verified by tests in locations with other geological settings. However, the results are encouraging and indicate that acoustic sounding has the potential of a new, complementary investigation method for investigation of hard soils and rock.

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